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Durability of concrete beams externally reinforced with composite fabrics

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This study represents the second half of a research project at the University of Delaware concerning the flexural strengthening of concrete beams using externally applied composite fabrics. Initial results showed that significant increases in flexural capacity can be achieved by epoxy-bonding composite fabrics to the tension face of reinforced concrete beams. This paper deals with the environmental durability of the concrete-epoxy fabric system. The three types of fabric studied are made of aramid, E-glass and graphite fibres. To determine the durability of this type of strengthening procedure under aggressive environments, 48 small-scale reinforced-concrete beams were exposed to freeze/thaw or wet/dry cycling in a calcium chloride solution, and an additional 12 beams were left in a control environment. Of the 60 beams, 45 were reinforced with aramid, E-glass, and graphite composite fabrics (15 with each type), and 15 had no external reinforcement (unwrapped). By varying the time of exposure to the different conditions and loading the beams to failure following the environmental testing, the durability of the externally reinforced beams was assessed. The tests indicate that chloride exposure in both wet/dry and freeze/thaw environments causes degradation to the beams' strength, with the wet/dry condition being slightly more severe. Both conditions led to some deterioration of the bond between the composite fabric and the concrete. Of the three types investigated, the graphite-reinforced beams proved to be the most durable, losing less than 15% of their 140% strength increase over the unwrapped beams after 100 cycles of exposure.

Keywords: durability; composites; concrete

The alarming deterioration of our world's infrastructure has caused engineers to seek new ways of rehabilitating aging structures. The utilization of advanced composite materials shows great potential in the area of structural rehabilitation. These new, high-performance materials have the advantages of being noncorrosive, generally resistant to chemicals, nonmagnetic and nonconductive. In addition, they possess a very high strength-to-weight ratio.

Several researchers have presented potential applications of composite materials for civil structures[1-9]. Still others have conducted specific experimental and analytical studies showing the effect of bonding composite-material plates to beams and wrapping concrete columns with composite jackets[10-20].

Recent work at the University of Delaware has focused on the flexural and shear strengthening of reinforced concrete beams using externally applied composite fabrics[21,22]. The research involved evaluating the use of fabrics made of aramid, E-glass and graphite fibres.

In the flexural strengthening study[21], 14 1.2-m-long by 127-mm-wide by 76.2-mm-high rectangular reinforced-concrete beams were tested. The beams, designed to satisfy the ACI ductility requirement[23] (i.e under-reinforced), were internally reinforced with one No. 3 Grade 60 steel bar. Nine of the beams were externally reinforced with composite fabric (three with one layer of aramid, three with two layers of graphite and three with three layers of E-glass fabric). The fabric was bonded to the beams using a two-part epoxy and in each case had a tensile capacity close to the yield strength of a single No. 3 bar (fabric strength ranged from 16 to 29% lower than a No. 3 bar). In addition to the nine externally reinforced beams, three more were left without external reinforcement (control), and two were internally reinforced with two No. 3 bars. The beams were loaded to failure in four-point bending and results indicated that external reinforcement can lead to increased flexural capacity similar to that achieved through additional internal reinforcement. The aramid, E-glass- and graphite-reinforced beams displayed increases in flexural capacities of 45.9, 41.2 and 43.1%, respectively, over the control beams, while the beams having two No. 3 bars were 62.8% stronger than the control beams.

In the shear strengthening study[22], 12 1.2-m-long reinforced-concrete T-beams were tested. The beams, designed to fail in shear, were internally reinforced with one No. 5 Grade 60 steel bar (15.875 mm diameter and a yield strength of 413 MPa). No transverse reinforcement was used. To study the effect of external reinforcement on shear capacity, one layer of aramid,

E-glass, or graphite fabric was bonded to each beam's web. The T-beams were loaded to failure, and their behaviours were compared to beams not reinforced with composite fabric. The tests showed that externally applied composite fabric can be used to increase the shear capacity of reinforced concrete beams. For the beams tested, external reinforcement led to increases in ultimate strength ranging from 60 to 150% over that of beams having no external reinforcement.

Both of these studies have shown that the application of externally bonded composite fabric reinforcement can lead to significant increases in strength for concrete elements and may be an effective rehabilitation procedure. However, due to the fact that many applications would be outdoors, the durability of the concrete-epoxy-fabric system under aggressive environments such as exposure to deicing chemicals, moisture and large temperature changes must be studied.

To date, only a limited number of studies have been conducted regarding the durability of composite materials used as reinforcement for concrete structures[24–31]. This work is made up of both environmental durability and fatigue resistance studies. Most of the research deals with the durability of resin impregnated composite material rods used for flexural reinforcement of concrete members in place of traditional steel reinforcement. Studies involving glass-type reinforcement subjected to marine environments (saline and alkali attack) have shown that the composite reinforcement can lose its effectiveness in as little as six months inside precracked beams, and in 15 months in beams that are not precracked[24,25]. In contrast to glass fibre reinforcement, reinforcing rods made from aramid and carbon fibres have shown insignificant losses of strength when exposed to marine environments[26,27]. Fatigue studies involving glass reinforcement indicate that the effects of cyclical creep are highly dependent upon stress amplitude[28], while research involving aramid reinforcing rods has shown them to possess exceptional fatigue resistance[29]. Besides composite rods, the durability of fibre-reinforced plastic (FRP) grids has also been studied[30,31]. Results from one study have shown that beams reinforced with FRP grids display similar bending behaviour under cyclic loading as do beams with steel reinforcement[31]. Environmental studies involving FRP grid reinforcement are still ongoing[31].

All of these previous studies have dealt with composite materials used as internal reinforcement of concrete structures. In this study, the environmental durability of externally applied composite-fabric reinforcement was evaluated using two different test procedures. Both tests were designed to examine the effect of a deicing-type chemical on the fabric-reinforced concrete beams. The first test was conducted under freeze/thaw conditions, while the second involved repeated wetting and drying.

Experimental study

Test program

The experimental program consisted of testing 60 small-scale reinforced-concrete beams. In addition to internal steel reinforcement, some of the beams had external composite reinforcement bonded to their tension faces. The beams were exposed to wet/dry and freeze/thaw conditions while sitting in a solution of calcium chloride. Once the beams had completed the environmental cycling, they were loaded to failure in four-point bending. By varying the number of cycles prior to load testing, the effects of chloride exposure during freezing and thawing, and wetting and drying, were evaluated.

Table 1 Concrete strengths

Concrete batch	Ultimate strength $f'c$ (MPa)
#1	26.9
#2	27.2
#3	34.2
#4	34.2
#5	33.8

Test specimens

The 60 beams used were fabricated in five batches, with each batch consisting of 12 beams. Along with each batch of beams, nine cylinders (50.8 mm in diameter × 101.6 mm high) were also cast. A concrete mix having a water-cement ratio of 0.50 by weight was used. The mix consisted of water, Type I Portland cement and aggregate having a maximum size of 3.175 mm. The beams were allowed to cure in a water bath for 28 days. The resulting concrete compressive strengths are shown in *Table 1*. The average strength of the five batches was 31.3 MPa, and none differed by more than 14% from this average.

Each beam had a length of 33.0 cm and cross-sectional dimensions of 38.1 mm × 28.6 mm (see *Figure 1*). The internal, longitudinal steel reinforcement was selected to satisfy the ACI ductility requirement ($200/f_y \leq \rho_b \leq 0.75\ \rho_b$)[23]. As a result, a single 2.38-mm-diameter, low-carbon, all-thread rod was used. The tensile stress–strain behaviour of the low-carbon all-thread rod

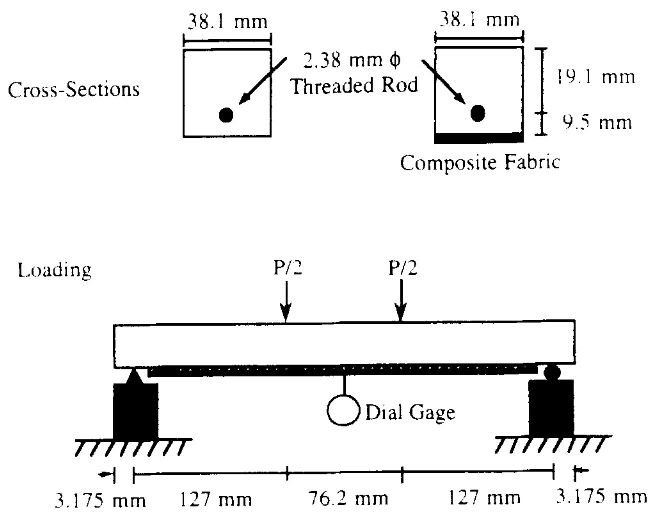

Figure 1 Test set-up

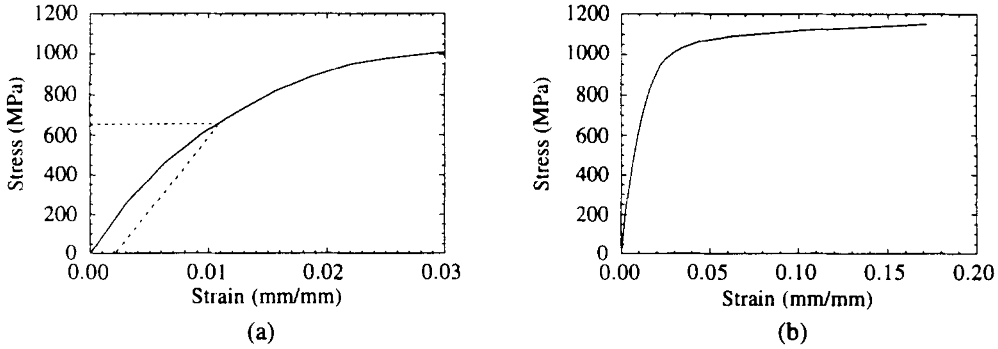

Figure 2 Stress–strain behaviour of reinforcing steel: (a) 0.2% offset; (b) full range

is shown in *Figure 2.* From the curve, the 0.2% offset yield strength was computed to be 658.5 MPa. It should be noted that this steel has a less defined yield point than typical Grade 60 rebar.

In addition to internal reinforcement, nine beams from each batch were externally reinforced with composite fabric (three with one layer of aramid fabric, three with one layer of E-glass fabric, and three with one layer of graphite fabric), and three were left without external reinforcement (later referred to as 'unwrapped'). A matrix of the beams tested is shown in *Table 2.*

Composite fabrics

The three specific types of composite fabrics used in this study were (1) plain-weave aramid fabric, (2) crowfoot satin-weave E-glass fabric and (3) plain-weave graphite fabric. All fabrics comprised fibres oriented at 0° and 90°. The tensile properties of a single layer of epoxy-impregnated fabric for each of the three types are presented in *Table 3*, while the stress–strain behaviour of each fabric is given in *Figure 3. Figure 3* shows that the response of the composite fabrics is basically linear-elastic to failure. For the 38.1-mm-wide beams, one layer of aramid, E-glass and graphite fabric will provide up to 8875 N, 2990 N and 4134 N of tensile capacity respectively.

Adhesive selection

As in the prior studies involving flexural and shear strengthening of reinforced concrete beams using externally bonded composite fabrics[21,22], a two-component, high-modulus, high-strength, room-temperature curing, construction-grade epoxy was used to bond the fabric to the concrete beams. Previous testing has shown that single layers of aramid, E-glass and graphite fabrics can be expected to develop full tensile capacity in approximately 25 mm for both E-glass and graphite fabric and in approximately 75 mm for the aramid fabric[22]. This rate of development was deemed acceptable for this study.

Due to the fact that some of the beams would be undergoing extreme temperature cycling, procedures given in ASTM C884-87[32] were used to check the epoxy–concrete compatibility. Twelve beams like those used in the durability studies (see *Figure 1*) were coated with adhesive along one face and allowed to cure. The beams were then placed in a freezer (–17°C) for 24 h and then removed from the freezer and left at room temperature for another 24 h. This cycle was repeated five times, after which the beams were examined. Since no cracking or debonding of the adhesive was noticed, the epoxy was deemed to be thermally compatible with the concrete.

Bonding of composite fabric

Before bonding the fabric to the beams, the concrete surface was mechanically abraded using a grinding wheel. This created a somewhat porous surface like that achieved by sandblasting. The fabric was coated with adhesive on both sides and placed onto the tension face of the beam, which itself had been coated with adhesive. The fabric was then smoothed to ensure a uniform distribution of adhesive and placed in a vacuum bag. The beam was allowed to cure under vacuum for one day, and for an additional two days once it was removed from the vacuum.

Test procedures

The objective of the environmental testing was to determine the effects of a calcium chloride solution on externally reinforced concrete beams under wet/dry and

Table 2 Beams tested

Batch	Environmental condition	Unwrapped beams	Aramid reinforced beams	E-glass reinforced beams	Graphite reinforced beams
#1	'Control'	3	3	3	3
#2	50 freeze/thaw cycles	3	3	3	3
#3	100 freeze/thaw cycles	3	3	3	3
#4	50 wet/dry cycles	3	3	3	3
#5	100 wet/dry cycles	3	3	3	3

Table 3 Properties of epoxy-impregnated composite fabrics

Composite fabric	Specimen thickness (mm)	Modulus of elasticity E_f (MPa)	Failure strain ε_{fu} (mm/mm)	Failure stress σ_{fu} (MPa)
Aramid	1.04	11 020	0.0225	223
E-glass	0.457	14 260	0.0134	171
Graphite	0.584	20 940	0.0095	185

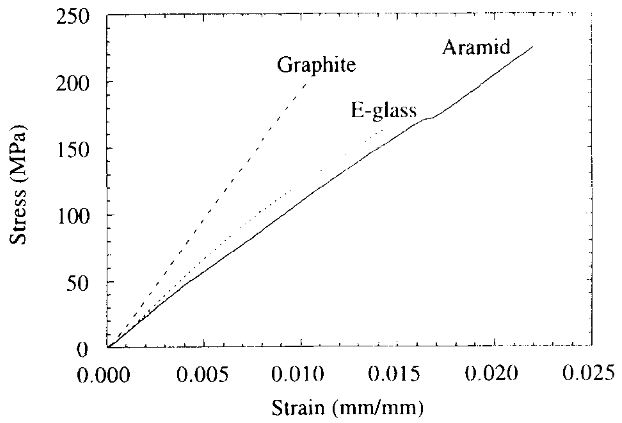

Figure 3 Stress–strain behaviour of epoxy-impregnated composite fabrics

freeze/thaw conditions. To accomplish this objective, two sets of tests were performed.

The first test (freeze/thaw cycling) followed the general procedures of ASTM C672-84[33]. In this test, the 24 beams from batches 2 and 3 were placed side-by-side in airtight containers with their compression side down (i.e. fabric side up), and covered with a calcium chloride solution consisting of 4 g anhydrous calcium chloride per 100 ml of water. The level of the solution was approximately 0.5 cm over the top of the beams. The beams were then subjected to repeated freeze/thaw cycling. Each cycle consisted of 16 h in a freezer at −17°C followed by 8 h of thawing at room temperature. Batch 2 underwent 50 cycles, while batch 3 underwent 100 cycles. After the beams had completed the designated number of cycles of exposure, they were loaded to failure in four-point bending using a 133 500 N Tinius Olsen universal testing machine (see *Figure 1*). During the loading, midspan deflections were measured at 50 N increments using a dial gauge.

The second test involved cycling the 24 beams from batches 4 and 5 through wet and dry conditions at room temperature. For this test, the same concentration of calcium chloride solution as in the first test was used (4 g anhydrous calcium chloride per 100 ml of water). A single wet/dry cycle consisted of placing the beams into the solution in airtight containers (side-by-side with their compression side down) so that they were covered by roughly 0.5 cm of fluid. After sitting in the solution for 16 h, the beams were allowed to dry at room temperature for 8 h. A fan was used to ensure complete drying. As in the last test, one batch underwent 50 cycles (batch 4) and the other batch underwent 100 cycles (batch 5). After the cycling was complete, the beams were loaded to failure as in the prior test (see *Figure 1*), and midspan deflections were recorded.

The final batch of beams (batch 1) was used as a control. These 12 beams were not subjected to any adverse environmental conditions. Instead, they were allowed to sit in ambient conditions in the laboratory. These beams were tested to failure in the same manner as all of the other beams. The results from these 'control' beams are used as a baseline (zero cycles) for both the freeze/thaw and wet/dry tests.

Experimental results

The results of the 60 beam tests are summarized in *Table 4*. Both the failure mode for each group of three beams, as well as the ultimate strength of each beam, are presented. In the following sections, the test results will be discussed in detail.

Beam behaviour and failure mode

Load–deflection plots for typical beams from each type of environmental condition are shown in *Figures 4* and *5*. *Figure 4* compares the response of unwrapped, aramid-reinforced, E-glass-reinforced and graphite-reinforced beams for each type and duration of environmental exposure (note that these plots have the same scale on the *y*-axis). *Figure 5* compares the response of control beams having a specific type of reinforcement to the responses of identically reinforced beams exposed to 100 freeze/thaw and 100 wet/dry cycles (note that these plots do not have the same scale on the *y*-axis).

The responses shown in the two figures indicate that the steel reinforcement in the unwrapped control beam begins to yield at a load of approximately 500–600 N. For the externally reinforced control beams, the initiation of steel yielding occurs at 750–1000 N. The increased capacity of the control beams after initial yielding seen in *Figure 5(a)* is related to the fact that the steel used has a less dramatic yield plateau than typical rebar (see *Figure 2*). For the aramid- and graphite-reinforced beams, the initiation of yielding is not affected by the environmental conditions (see *Figure 5(b), (d)*). For the unwrapped and E-glass-reinforced beams, the onset of steel yielding occurs slightly earlier for the beams exposed to both environmental conditions (see *Figure 5(a), (c)*). The most significant effect occurs in the unwrapped beams exposed to 100 freeze/thaw cycles. These beams experienced some concrete spalling as a result of the repeated freezing and thawing. The spalling was most severe on the tension face (upper face during the exposure). By contrast, the fabric reinforcement helped to limit concrete spalling on the beams to which it was applied. After steel yielding, but prior to failure, the externally reinforced beams exhibit significantly greater stiffnesses than do the unwrapped beams (see *Figure 4*). The beams reinforced with aramid display the greatest stiffness, followed by the graphite and E-glass beams. While this post-yield stiffness remained relatively unchanged for the E-glass beams regardless of the type of environmental exposure

Table 4 Beam test results

Reinforcement	Failure mode	Ultimate beam strength (N) Beam 1	Beam 2	Beam 3
Control ($f'c$ = 26.9 MPa)				
Unwrapped	Ductile flexural failure	1135	1225	1250
Aramid	Concrete shear failure	3337	3525	3650
E-glass	Fabric tensile failure	2175	2275	2350
Graphite	Fabric tensile failure	2915	2925	2780
50 freeze/thaw cycles ($f'c$ = 27.2 MPa)				
Unwrapped	Ductile flexural failure	1050	1000	1050
Aramid	Fabric debonding	2865	1975	2985
E-glass	Fabric tensile failure	1900	1850	2045
Graphite	Fabric tensile failure and partial debonding	2665	2215	2195
100 freeze/thaw cycles ($f'c$ = 34.2 MPa)				
Unwrapped	Ductile flexural failure	1000	1000	1000
Aramid	Fabric debonding	3260	2835	3455
E-glass	Fabric tensile failure	1605	1845	1545
Graphite	Fabric tensile failure and partial debonding	2375	2315	2110
50 wet/dry cycles ($f'c$ = 34.2 MPa)				
Unwrapped	Ductile flexural failure	1075	1000	1060
Aramid	Fabric debonding	2600	3100	2710
E-glass	Fabric tensile failure	1600	1435	1330
Graphite	Fabric tensile failure and partial debonding	2485	2557	2730
100 wet/dry cycles ($f'c$ = 33.8 MPa)				
Unwrapped	Ductile flexural failure	1015	1060	1100
Aramid	Fabric debonding	2475	2105	2130
E-glass	Fabric tensile failure	1463	1413	1465
Graphite	Fabric tensile failure and partial debonding	2330	2515	2150

(see *Figure 5(c)*), it was somewhat reduced for the aramid and graphite beams (see *Figure 5(b), (d)*).

Failure modes did not change due to the different conditions for either the unwrapped or E-glass-reinforced beams (see *Table 4*). All of the unwrapped beams experienced ductile flexural failure, while all of the E-glass beams failed as a result of the tensile failure (tearing) of the fabric. For the beams reinforced with graphite and aramid fabrics, the environmental conditions did, in some cases, affect the mode of failure. Fabric tearing initiated failure for the graphite beams in the control batch, and excellent adherence of concrete to the epoxy-bonded fabric was observed. After exposure to both freeze/thaw and wet/dry conditions, the graphite beams showed signs of bond degradation just prior to the tensile failure of the fabric. Bond degradation was also observed in the case of the aramid beams, which failed due to shearing of the concrete in the control batch, but debonded in almost every other case (wet/dry and freeze/thaw). Examination of the graphite and aramid beams after failure indicated that the environmental conditions had begun to deteriorate the concrete-epoxy-fabric bond. For the cases where deterioration of the bond was observed, the adherence of concrete to the fabric was greatly reduced from the adherence observed in the control beams. It is important to recall that the 38.1-mm-wide aramid, E-glass and graphite fabrics have tensile capacities of 8875, 2990 and 4134 N respectively. As a result, a higher bond strength is required to fully develop the aramid fabric than the graphite or E-glass fabrics. If the bond is indeed degraded by the environmental conditions, we would expect to see debonding in the aramid beams first, followed by the graphite and then the E-glass beams.

Effect of environmental conditions on ultimate strength

Figure 6, along with *Tables 5–7*, helps to summarize the change in ultimate beam strength caused by the environmental exposure. *Figure 6* provides an overall illustration of the effect of the number of cycles of exposure on the ultimate beam strength for each type of environmental condition and each type of external reinforcement. *Table 5* presents the average beam strength for each type of reinforcement for each of the five conditions. *Table 6* presents the percentage reduction from the control values in the average beam strength, caused by the freeze/thaw and wet/dry cycling. Finally, for each environmental condition, *Table 7* presents the percentage increase in strength over that of the unwrapped beams, caused by the three types of external reinforcement.

For both the unwrapped and the fabric-reinforced beams, exposure to each of the environmental conditions had an adverse effect on their ultimate strengths (see *Figure 6* and *Tables 5* and *6*). Prior to being exposed to the environmental conditions (control batch), the aramid-, E-glass- and graphite-reinforced beams were on average 191, 88 and 139% stronger than the unwrapped beams (see *Table 7*). As a result of exposure to the two environments, a definite trend of increasing degradation of beam capacity with increased exposure can be seen (*Figure 6*). The only exception occurred in the case of the aramid-reinforced beams

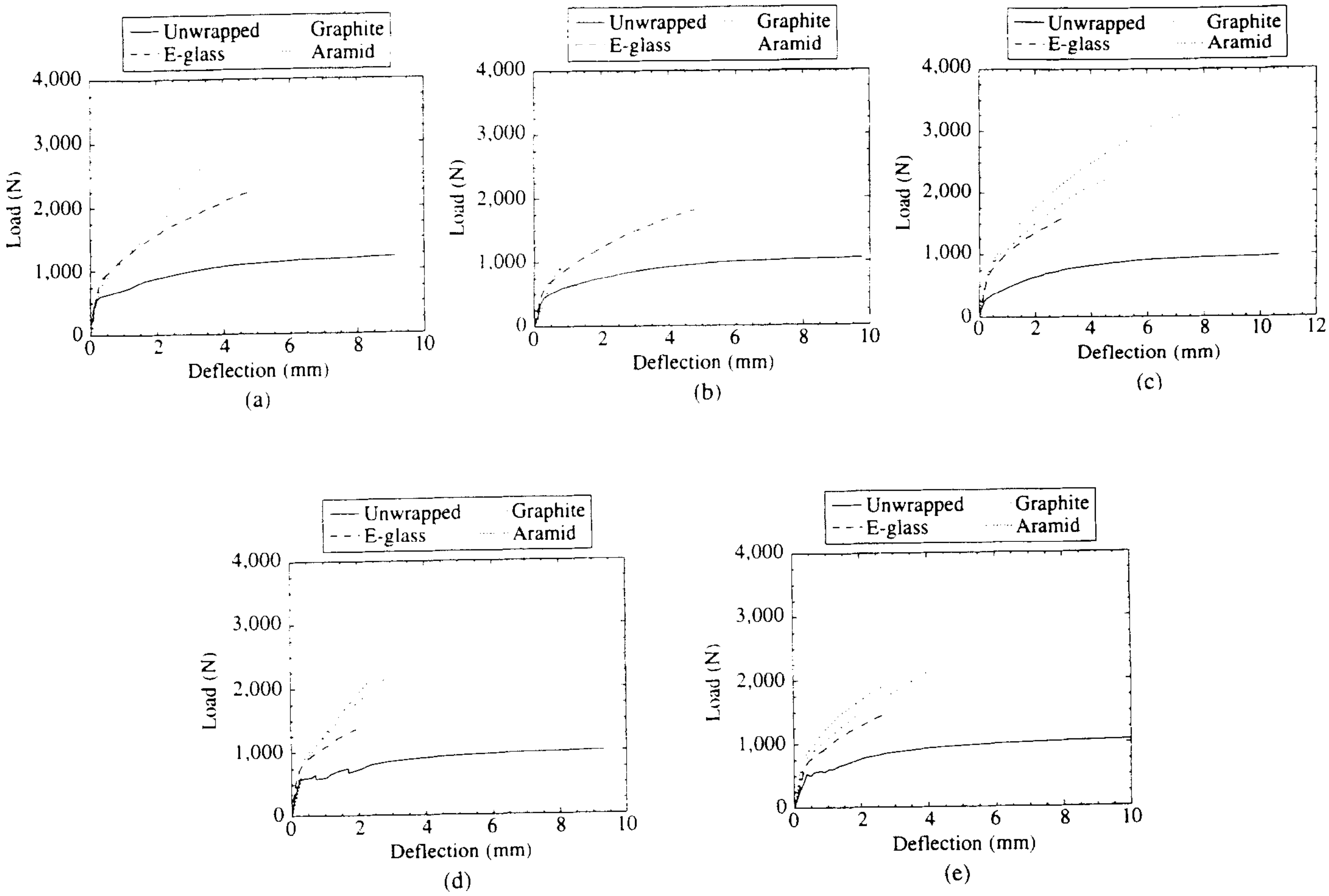

Figure 4 Load-versus-midspan deflection for beams having identical exposure type and duration, but varied reinforcement: (a) control beams; (b) 50 freeze/thaw cycles; (c) 100 freeze/thaw cycles; (d) 50 wet/dry cycles; (e) 100 wet/dry cycles

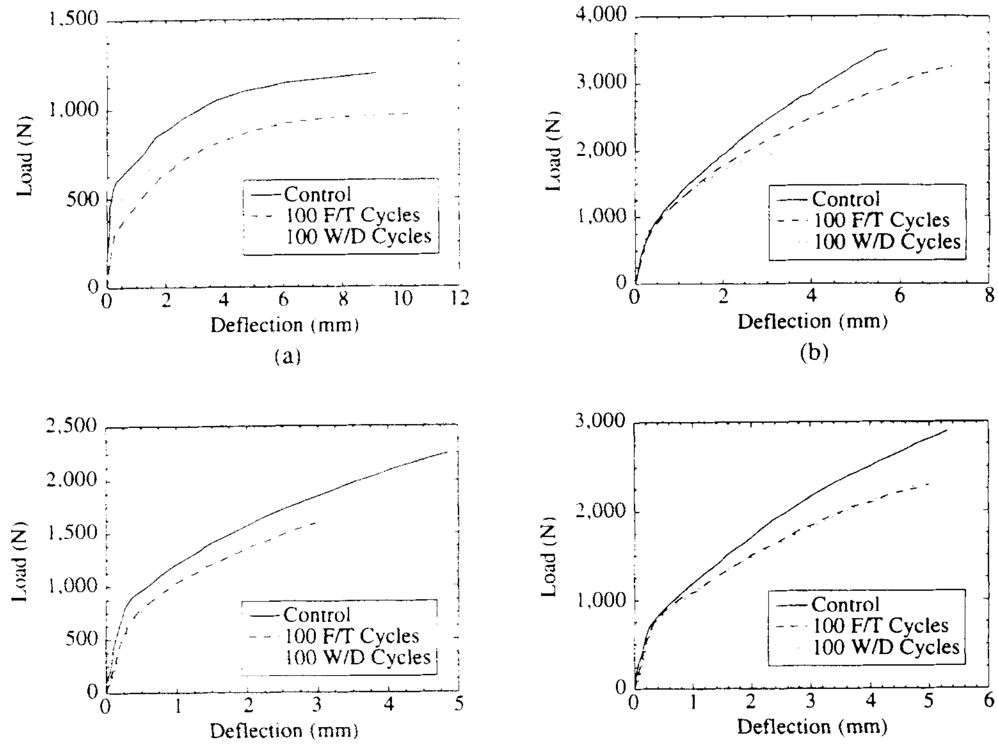

Figure 5 Load-versus-midspan deflection for beams having identical reinforcement, but varied exposure types and duration: (a) unwrapped beams; (b) aramid-reinforced beams; (c) E-glass-reinforced beams; (d) graphite-reinforced beams

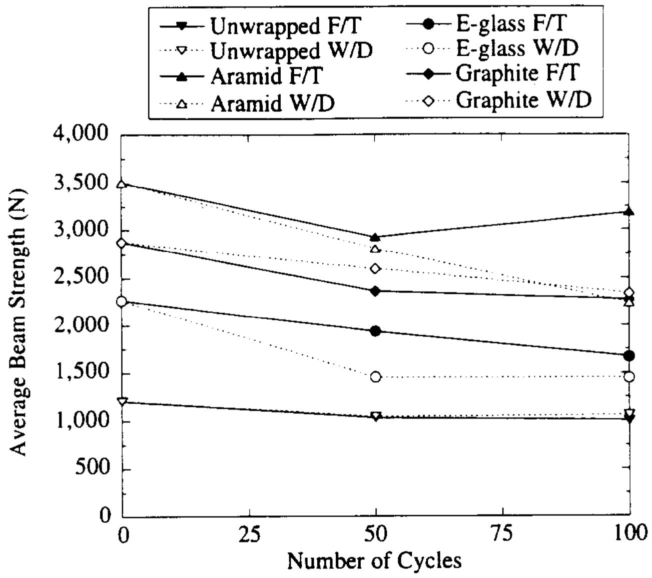

Figure 6 Effect of number of cycles on ultimate beam strength

Table 5 Average beam strength

Environmental condition	Unwrapped (N)	Aramid (N)	E-glass (N)	Graphite (N)
Control	1203	3504	2267	2873
50 cycle freeze/thaw	1033	2295[a]	1932	2358
100 cycle freeze/thaw	1000	3183	1665	2267
50 cycle wet/dry	1045	2803	1455	2591
100 cycle wet/dry	1058	2237	1447	2332

[a] Beam 2 of this set was not used in calculating the average

Table 6 Decrease in beam strength due to environmental conditions

Environmental condition	Unwrapped (%)	Aramid (%)	E-glass (%)	Graphite (%)
Control	–	–	–	–
50 cycle freeze/thaw	14	17	15	18
100 cycle freeze/thaw	17	9	27	21
50 cycle wet/dry	13	20	36	10
100 cycle wet/dry	12	36	36	19

Table 7 Increase in beam strength due to external fabric

Environmental condition	Unwrapped	Aramid (%)	E-glass (%)	Graphite (%)
Control	–	191	88	139
50 cycle freeze/thaw	–	183	87	128
100 cycle freeze/thaw	–	218	67	127
50 cycle wet/dry	–	168	39	148
100 cycle wet/dry	–	111	37	120

exposed to 100 freeze/thaw cycles. While these beams had a lower capacity than their corresponding control beams, they were stronger than the aramid beams exposed to 50 freeze/thaw cycles. This can be partially explained by the 26% difference in concrete strength between these two batches.

Both *Table 6* and *Figure 5* indicate that the wet/dry cycling had a slightly more severe effect on the ultimate strength of the externally reinforced beams than did the freeze/thaw cycling. This was especially true for the aramid beams which lost only 9% of their original strength after 100 freeze/thaw cycles, but lost 36% of their strength after 100 wet/dry cycles. For the unwrapped beams, the freeze/thaw cycling was slightly more severe, with the beams losing 17% of their original strength after 100 cycles.

Of the three fabrics themselves, the E-glass seemed to degrade the most as a result of the environmental exposure. While both the control and exposed E-glass-reinforced beams failed due to tensile failure of the fabric, the capacity of beams exposed to 100 wet/dry cycles dropped by 36%. This drop in capacity is directly related to a drop in tensile capacity of the fabric. The deterioration of the glass fibre fabric is consistent with the studies cited earlier involving glass reinforcement exposed to marine environments[24,25].

Possibly the most significant observation with regard to ultimate strength is that the beams reinforced with graphite fabric were noticeably less affected by the environmental conditions than those reinforced with aramid and E-glass fabrics. While both the aramid- and E-glass-reinforced beams showed a 36% decrease in strength due to 100 wet/dry cycles, the graphite-reinforced beams dropped in strength by only 19% (as compared to the 12% drop in strength of the unwrapped beams subjected to wetting and drying). Using another method of comparison (see *Table 7*), it is evident that only the graphite-reinforced beams maintained nearly all of their strength advantage over the unwrapped beams. While all of the wrapped beams remained stronger than their unwrapped counterparts, after 100 wet/dry cycles, the increase in strength over the unwrapped beams dropped from 191 to 111% for the aramid beams and from 88 to 37% for the E-glass beams. By contrast, the graphite beams, which were 139% stronger than the control beams initially, were still 127% stronger after 100 freeze/thaw cycles and 120% stronger after 100 wet/dry cycles.

Conclusion

The durability studies conducted show that reinforced concrete beams strengthened by externally bonded aramid, E-glass and graphite fabrics experience varying degrees of degradation due to aggressive environments. Initially, external composite reinforcement led to significant increases in beam strength. While the composite-fabric-reinforced beams remain stronger than their unreinforced counterparts, exposure to chlorides under both wet/dry and freeze/thaw environments led to reduced ultimate beam strengths. Of the three fabrics tested, both aramid and E-glass lost roughly half of their strength advantage after environmental exposure. On the other hand, the graphite reinforced beams, which initially displayed a 139% increase in strength over the unwrapped beams, maintained a 127% strength increase after 100 freeze/thaw cycles, and a 120% increase after 100 wet/dry cycles. Overall, of the two conditions tested, the wet/dry environment was found to cause slightly greater degradation.

In addition to the reduction in ultimate strength of the beams, the tests show that degradation caused by exposure to aggressive environments can lead to changes in the failure mode of the beams. While debonding was not a problem for the control beams, all of the exposed aramid-reinforced beams failed due to debonding of the fabric. Furthermore, inspection of the E-glass- and graphite-reinforced beams after failure indicated that deterioration of the concrete-epoxy-fabric bond had occurred, evidenced by the lack of adherence of concrete to the fabric.

It should be noted that the beams tested were small-scale specimens. By using the small-scale specimens, it was possible to subject a relatively large number of beams to a variety of environmental conditions and exposure times, thereby providing useful information regarding the relative degradation of the various types of reinforcement.

While additional full-scale durability studies are needed, these results indicate that graphite fabric reinforcement is least affected by environmental conditions and is better suited for applications involving exposure to deicing chemicals where repeated wetting and drying and/or freezing and thawing are expected to occur.

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